Positronium signature in organic liquid scintillators for neutrino experiments

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APC

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Why tagging positrons in scintillators

- **Anti-neutrinos** are commonly detected in scintillators via inverse beta decay:

$$\bar{\nu}_e + p \longrightarrow n + e^+ \longrightarrow \text{annihilation } (?)$$
$$n \longrightarrow \text{capture}$$

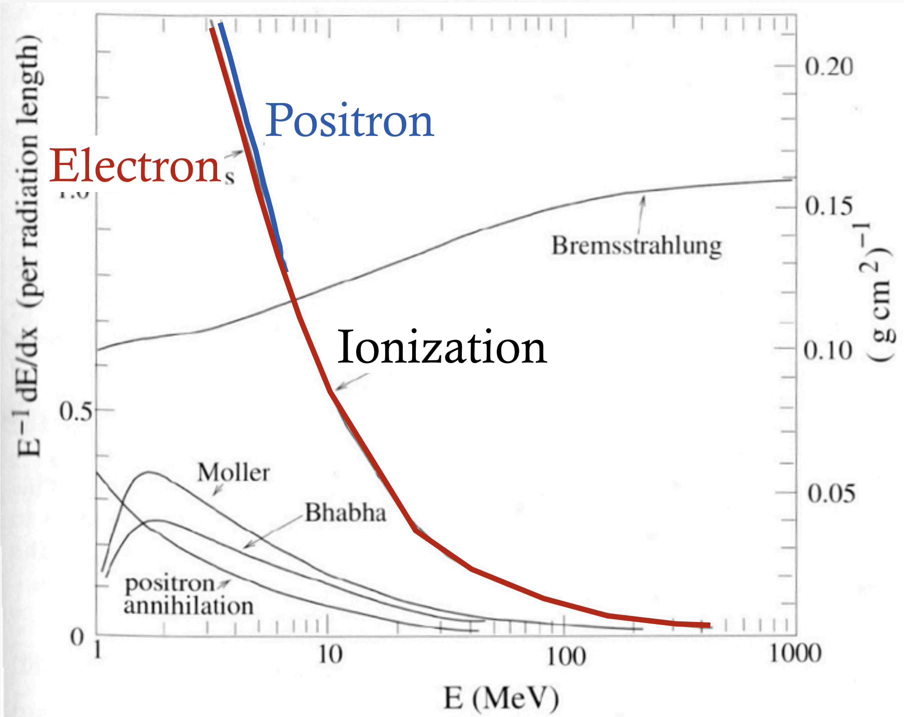
  - The signature is provided by the delayed e^+-n coincidence (tenth of μs)
  - e.g.: **Reactor anti-neutrino experiments** for measuring θ_{13} (**Double Chooz, Reno, Daya-Bay**) and detectors for reactor monitoring (**Nucifer, SONGS, …**) rely on the inverse beta decay signature, fighting with electron like background

- **Neutrinos** are detected via elastic scattering:

$$\nu_x + e^- \longrightarrow \nu_x + e^-$$

  - the signature relies on the energy distribution of the recoiled electron
  - e.g.: **Solar neutrino experiments** (**Borexino, SNO+, KamLAND**) have to face the background from cosmogenic ^{11}C (β^+) in order to measure the pep-ν rate

Standard PSD?



Pulse Shape Discrimination (**PSD**) for **e^+/e^-** may meet a general interest in the neutrino community

But scintillators have almost **equal response to e^+/e^-** in the energy region of interest (<10 MeV)

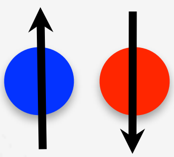
standard PSD can not be applied!!

No way (**up to now!**) to separate **electron** (positron) induced signal from **positron** (electron) background in scintillator

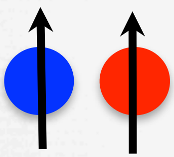
Exploiting positronium formation…

In matter **positrons** may either directly **annihilate** or form a **positronium** state

Positronium has two ground states:



para-positronium (p-Ps) mean life in vacuum of ~ 120 ps
singlet - 2 gamma decay



ortho-positronium (o-Ps) mean life in vacuum of ~ 140 ns
triplet - 3 gamma decay

In matter o-Ps has a **shorter mean life**, mainly because of:

- **spin-flip**: conversion to p-Ps due to a magnetic field
- **pick off**: annihilation on collision with an anti-parallel spin electron

Note!! the 3 body decay channel is negligible in matter

Even a **short delay** (**few ns**) in energy depositions **between positron** (via ionization) **and** annihilation **gammas** (via Compton scattering) can provide a **signature for tagging (a subset of) positrons**

Measuring o-Ps in liquid scintillators

D. Franco, G. Consolati, D. Trezzi, Phys. Rev. C83 (2011) 015504

Lab measurements of o-Ps **probability formation** and **lifetime** in liquid scintillators, presently used by **neutrino experiments**, with the Positron Annihilation Lifetime Spectroscopy (**PALS**) technique

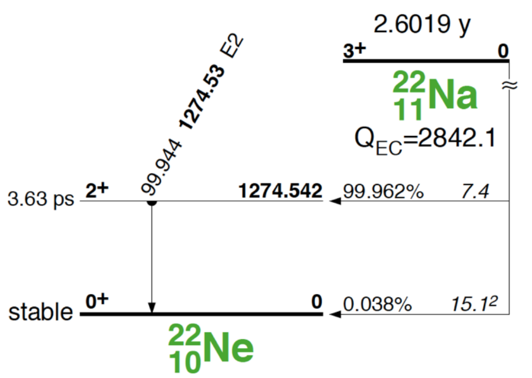
Experiment	Scintillator	Fluor	Dope
KamLAND	20% PC	1.5 g/l PPO	
	80% OIL		
Borexino	PC	1.5 g/l PPO	
LVD	Paraffin	1.0 g/l PPO	
SNO+	LAB	PPO	0.1% Nd
Double Chooz	20% PXE	3-6 g/l PPO	0.1% Gd
	80% OIL	20 mg/l Bis-MSB	
Daya Bay	LAB	3 g/l PPO	0.1% Gd
		15 mg/l Bis-MSB	
RENO	LAB	1-5 g/l PPO	0.1% Gd
		1-2 mg/l Bis-MSB	

Investigated in this set of measurements

Foreseen for the next campaign

The PALS technique

The ^{22}Na positron source:



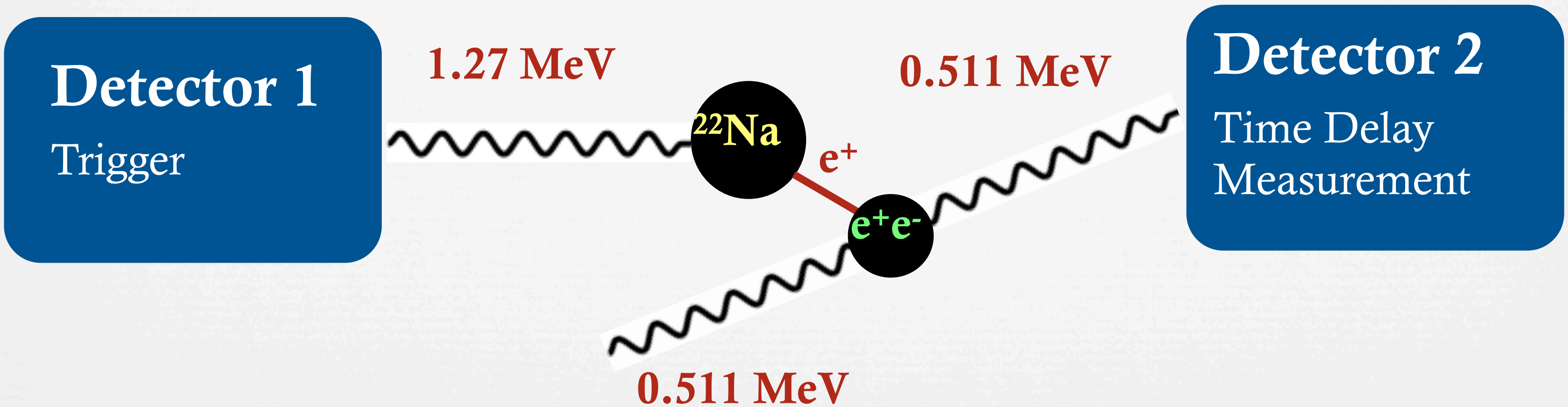
decays channel (BR ~ 99.9%): **e^+ + 1.27 MeV γ**

mean delay between e^+ and γ: **~ 3.6 ps**

activity: **0.8 MBq**

the source (few μm thick) is inserted between four 7.5 μm thick layers of **Kapton** (low o-Ps formation)

the "sandwich" is poured in a ~1 cm thick glass **vial** with the liquid scintillator



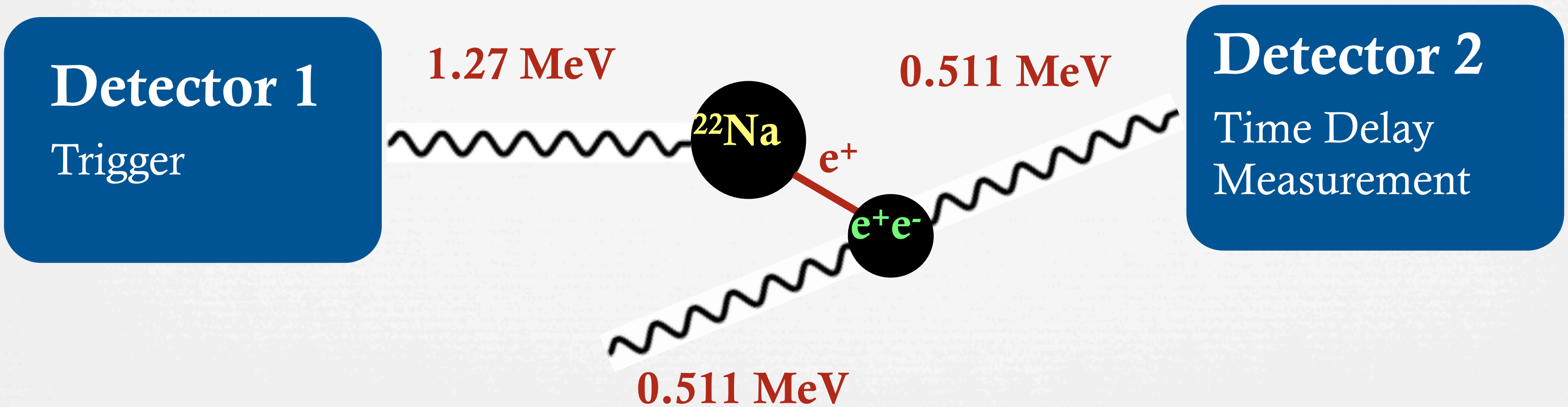
The PALS technique

Detectors are commercial plastics scintillators (**Pilot U**) coupled with PMTs

1.27 MeV gammas are selected with an energy cut > 0.9 MeV (trigger) on detector 1 (plastic scintillator thickness: 25 mm)

0.511 gammas are selected in the energy window [0.35-0.50] MeV (plastic scintillator thickness: 15 mm)

Electronics **calibrated with ^{60}Co**: 4096 channels, each corresponds to 10.6 ps



Data Analysis

1: annihilation or p-Ps
2: o-Ps

accidentals

$$F(t) = \chi(t > t0) \cdot \left(\sum_{k=1,2} \frac{A_k}{\tau_k} \cdot e^{-t/\tau_k} + C \right)$$

offset

convoluted with

resolution function: 2 gaussians

$$G(t) = \sum_{i=1,2} \frac{g_i}{\sqrt{2\pi\sigma_i^2}} \cdot e^{-\frac{t^2}{2\cdot\sigma_i^2}}$$

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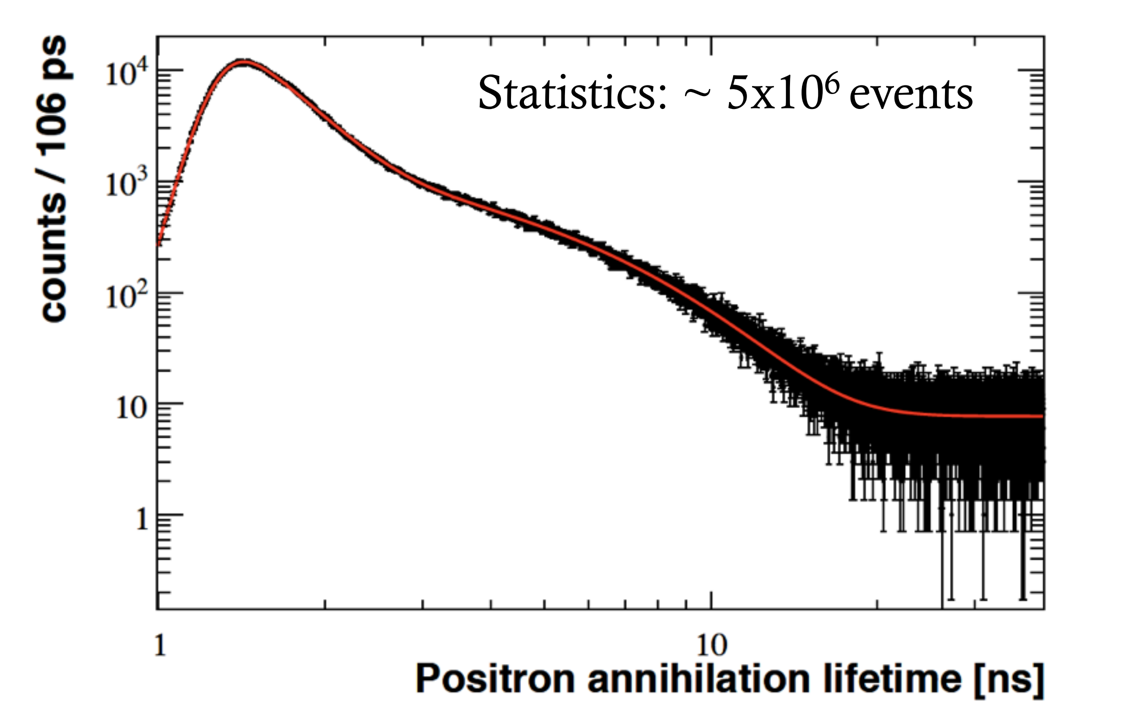
Each sample has been measured 3 times to take into account **systematic effects**

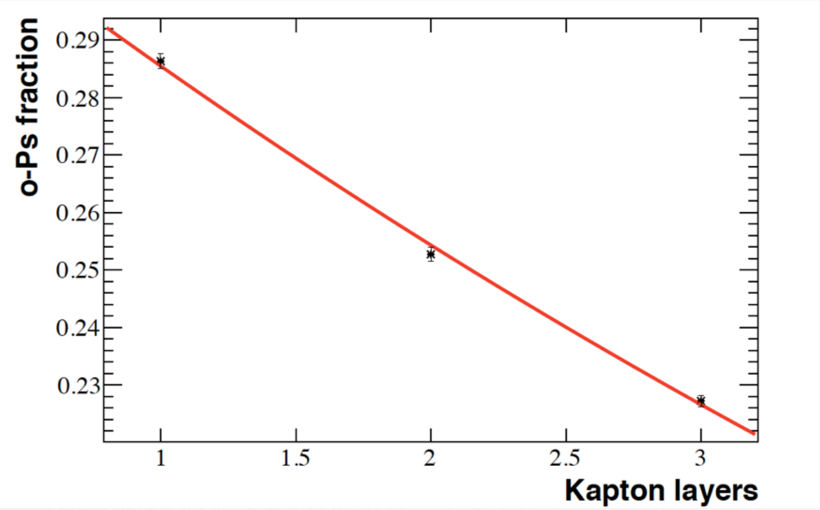
Detection efficiency checked with MC (Geant4-based)



o-Ps formation probability and lifetime

Estimation of o-Ps in Kapton

Sandwiches with 1-2-3 Kapton layers and Plexiglas (o-Ps $\tau \sim 2$ ns)



o-Ps probability formation in 2 layers of Kapton: 20.6 ± 0.2 %

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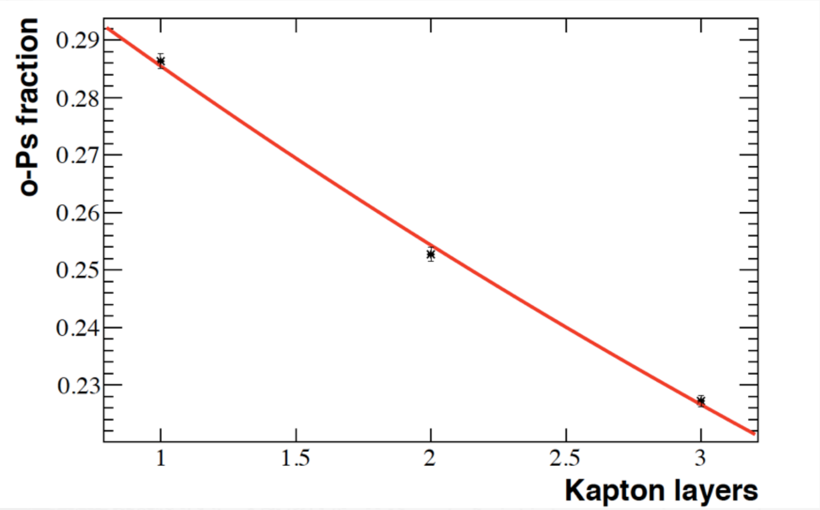


o-Ps probability formation in 2 layers of Kapton: 20.6 ± 0.2 %

$$p_2 = N_2 / (N_1 + N_2 - N_k)$$

where
1: annihilation / p-Ps
2: o-Ps
k: Kapton

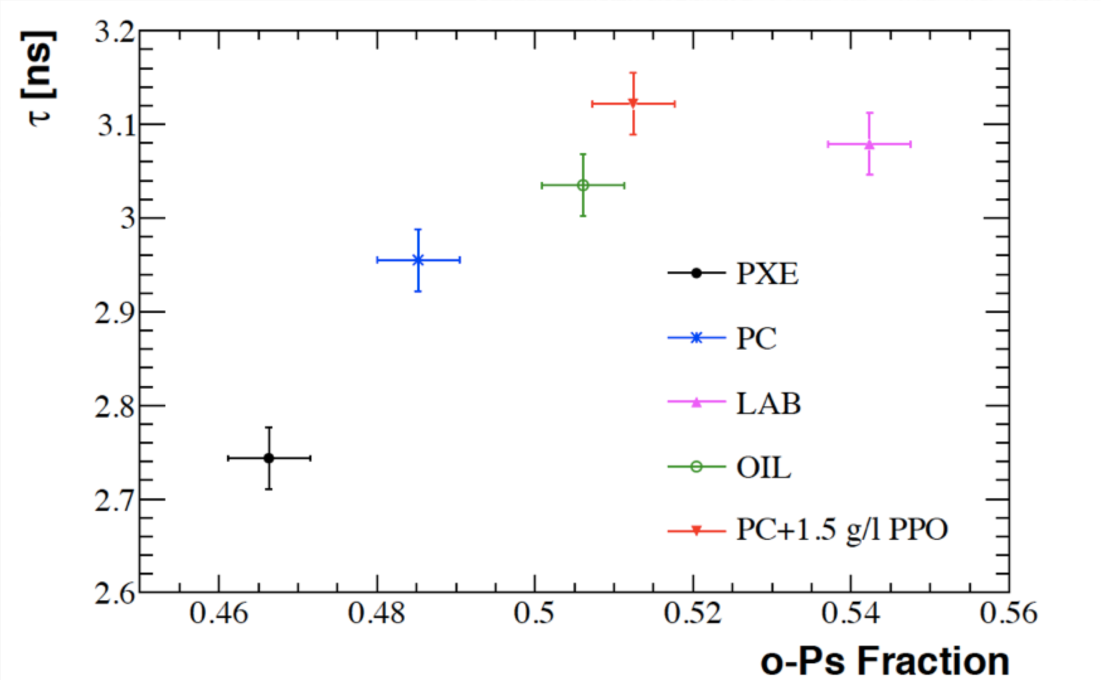
Fit results on scintillator samples

- mean τ_1 = **365 ± 8 ps**
- $\sigma_1 \sim$ **110 ps** ($g_1 \sim 0.8$)
- $\sigma_2 \sim$ **160 ps** ($g_2 \sim 0.2$)
- $\chi^2/\mathrm{ndf} \in$ **[0.85 - 0.98]**

Systematic errors:

- **o-Ps τ = 0.03 ns**
- **o-Ps p = 0.5%**

Results



- **opportunity to disentangle e^+/e^-:**

All samples have o-Ps **probability formation ~ 0.5** and **mean life ~ 3 ns**

- **can the technique be improved?**

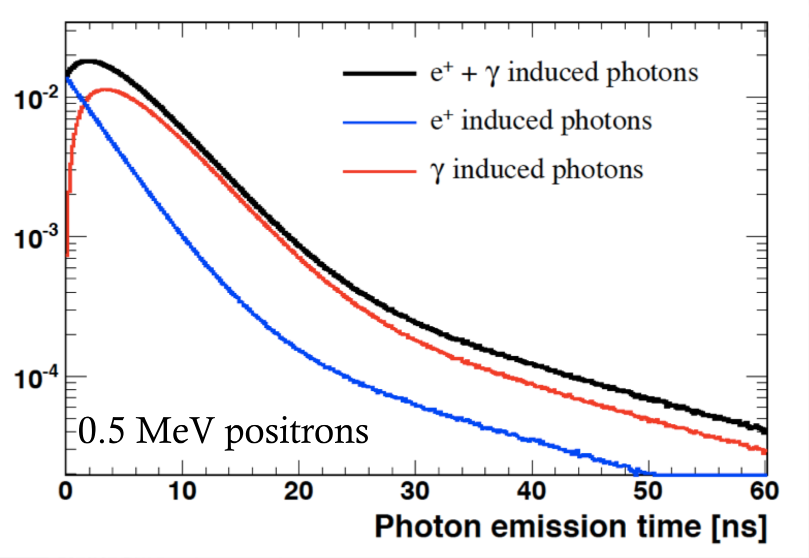
o-Ps characteristics in PC and PC+PPO have (slight) differences. **Can a doper increase o-Ps mean life and probability formation?**

Material	f_2	τ_2 [ns]
PXE	0.466 ± 0.005	2.74 ± 0.03
LAB	0.542 ± 0.005	3.08 ± 0.03
PC	0.485 ± 0.005	2.96 ± 0.03
OIL	0.506 ± 0.005	3.04 ± 0.03
PC+1.5 g/l PPO	0.512 ± 0.005	3.12 ± 0.03

Scintillator	τ_1 [ns]	τ_2 [ns]	τ_3 [ns]	N_1 %	N_2 %	N_3 %
PC + 1.5 g/l PPO	3.57	17.61	59.9	89.5	6.3	4.2
PXE + 1.0 g/l PPO	3.16	7.7	34	84.0	12.0	2.9
LAB + 1.0 g/l PPO	7.46	22.3	115	75.9	21.0	3.1

The o-Ps signature

Photon Emission Time



Ideal case, PC+1.5 g/l PPO, not including absorption and re-emission

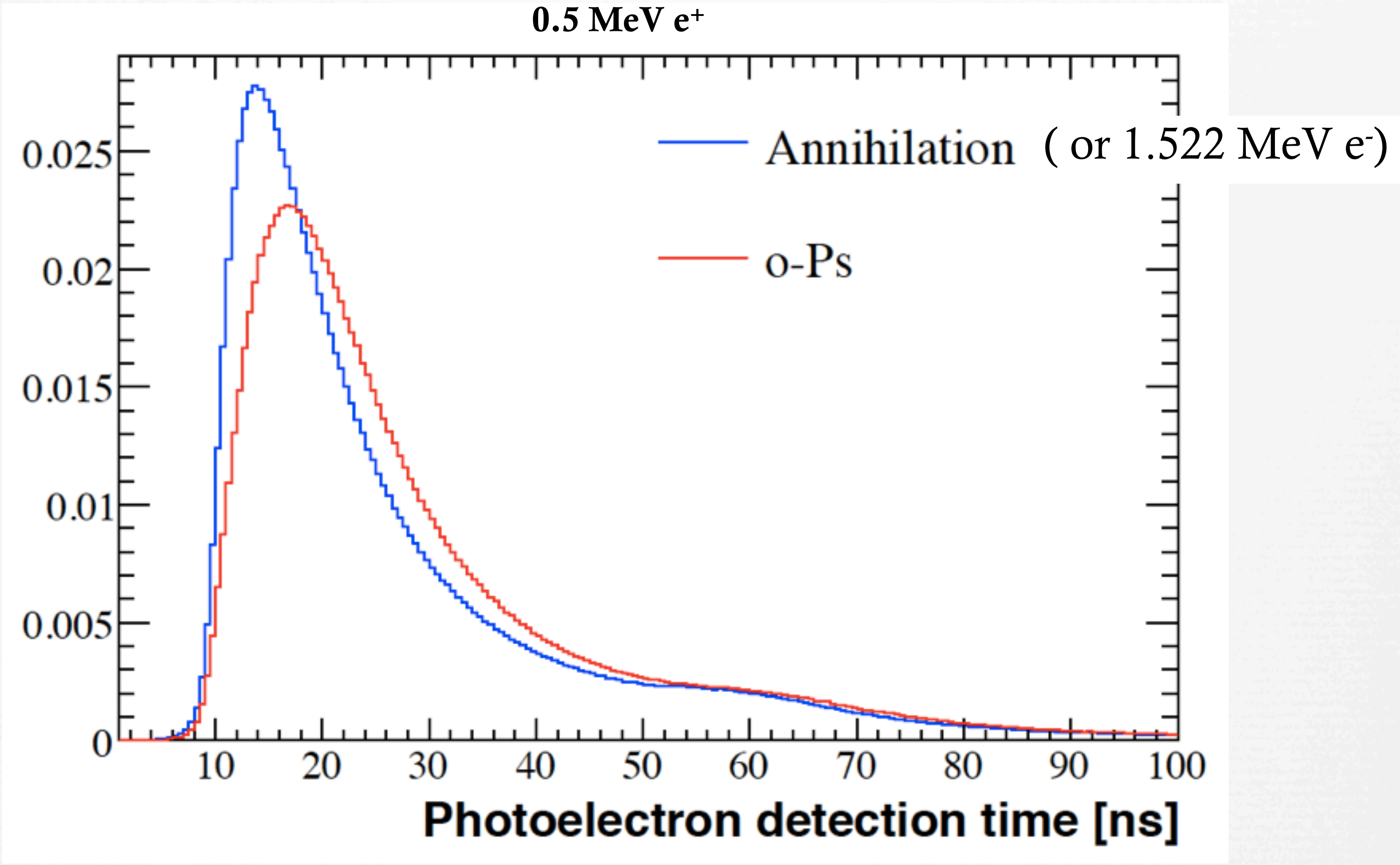
o-Ps signature

Photon emission time **distortion** due to the **delay** between photon emissions induced by **positron** ionization and by Compton electrons from annihilation **gammas**

MC simulation of an ideal detector

- Full **Monte Carlo simulation** (Geant4) to understand the effect of o-Ps on the Pulse Shape Discrimination
- Assuming an **ideal spherical detector** like Borexino/KamLAND/SNO+:
  - **4 m radius stainless steel sphere**
  - 2000 PMTs (**Jitter = 1.4 ns**)
  - no acrylic/nylon vessels
  - 10000 photons/MeV
  - **optical processes** (Rayleigh, reflections, absorption and re-emission,...)
  - PC + 1.5 g/l PPO (Borexino like)
  - Scintillation decay constants: $\boldsymbol{\tau_1 = 3.57}$ **ns** (89.5%), $\tau_2 = 17.61$ ns (6.3%), $\tau_3 = 59.9$ ns (4.2%) (*Borexino, Nucl. Instrum. Meth. A 584, 98 2008*)
  - Electronics with Flash ADC **1 GHz**
  - 1 kHz of noise on each PMT

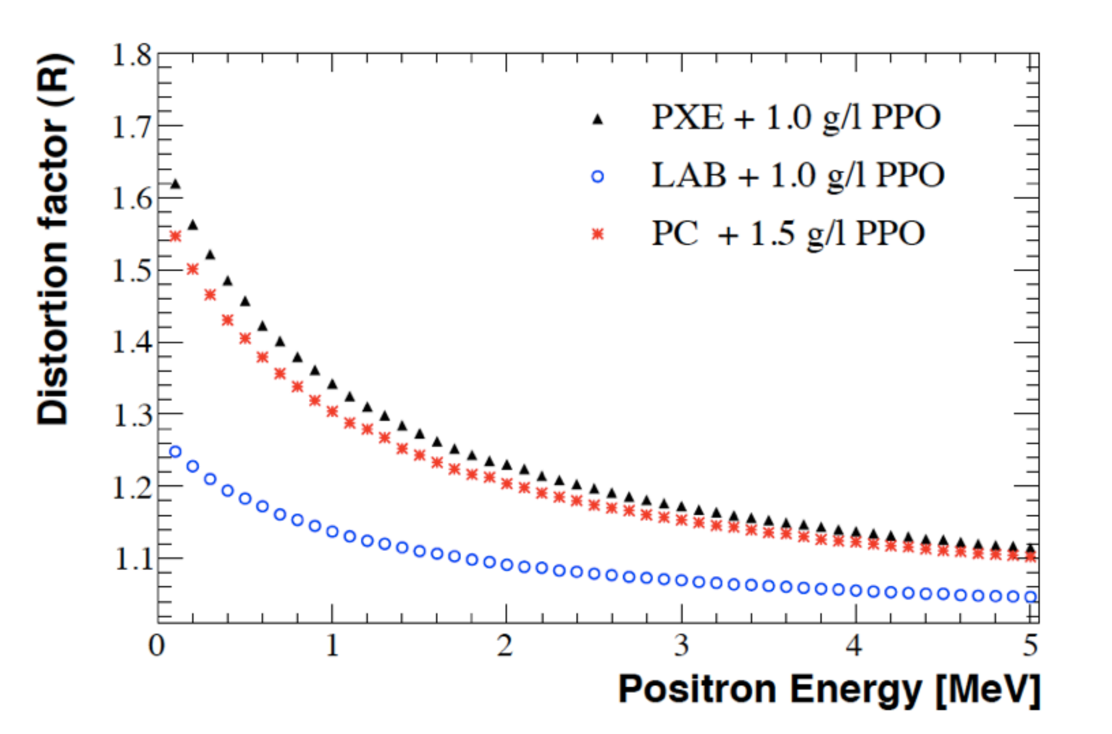
The Pulse Shape



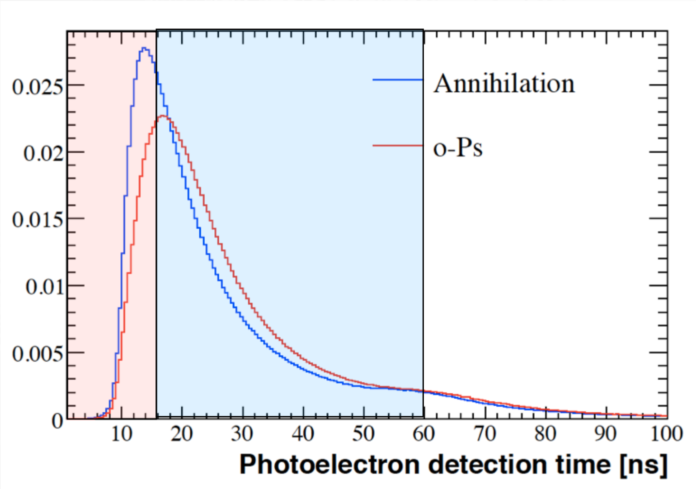
Including ALL the detection effects and Time Of Flight subtraction

The Energy Dependence

- The o-Ps pulse shape is the **sum of 2 distributions**
  - annihilation gammas, with **“FIXED”** number of p.e. $\propto$ quenched(2x511 keV)
  - positron ionization, with **“VARYING”** number of p.e. $\propto$ quenched (positron energy)
- The **relative weight** between the 2 distributions **varies with the positron energy**
- At **E_{e+} >> 1.022 MeV**, o-Ps and annihilation distributions coincide
- Estimator (**R**): ratio between mean times of annihilation and o-Ps distributions

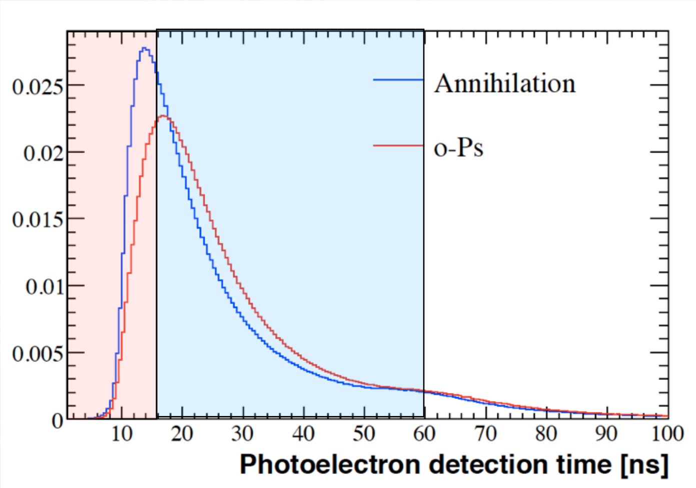


Pulse Shape Discrimination

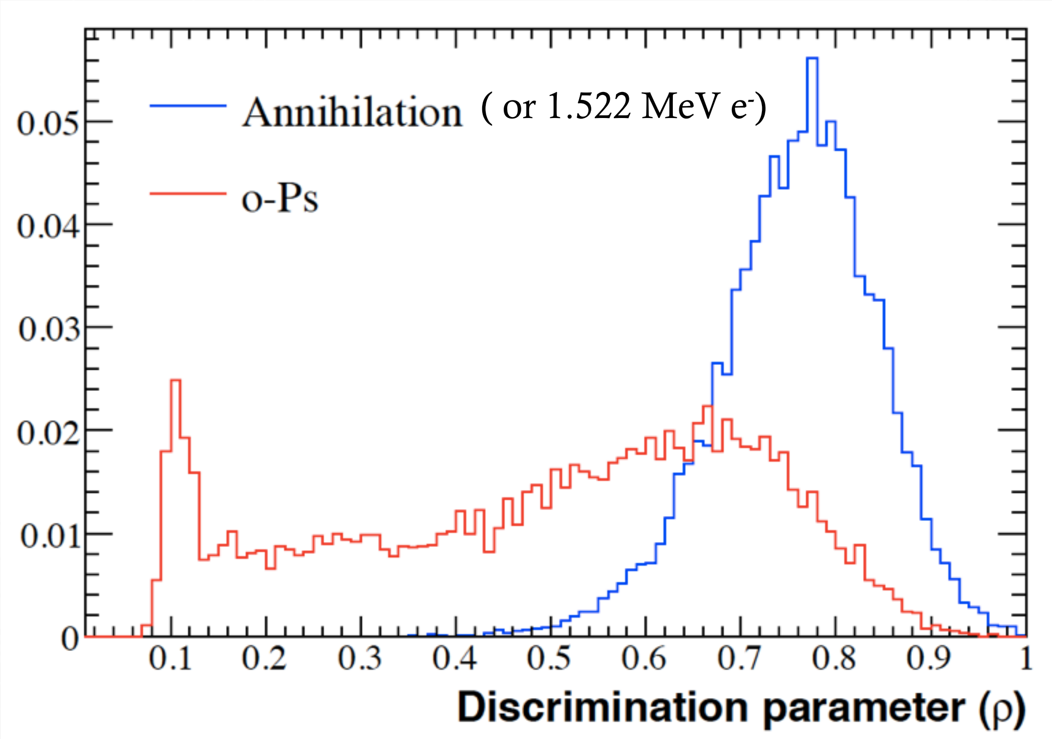


Estimator (ρ): ratio between numbers of p.e.'s in [0-18] ns and [18-60] ns

Pulse Shape Discrimination



Estimator (ϱ): ratio between numbers of p.e.'s in [0-18] ns and [18-60] ns



Good separation!!

at 0.5 MeV and ϱ < ~0.5:

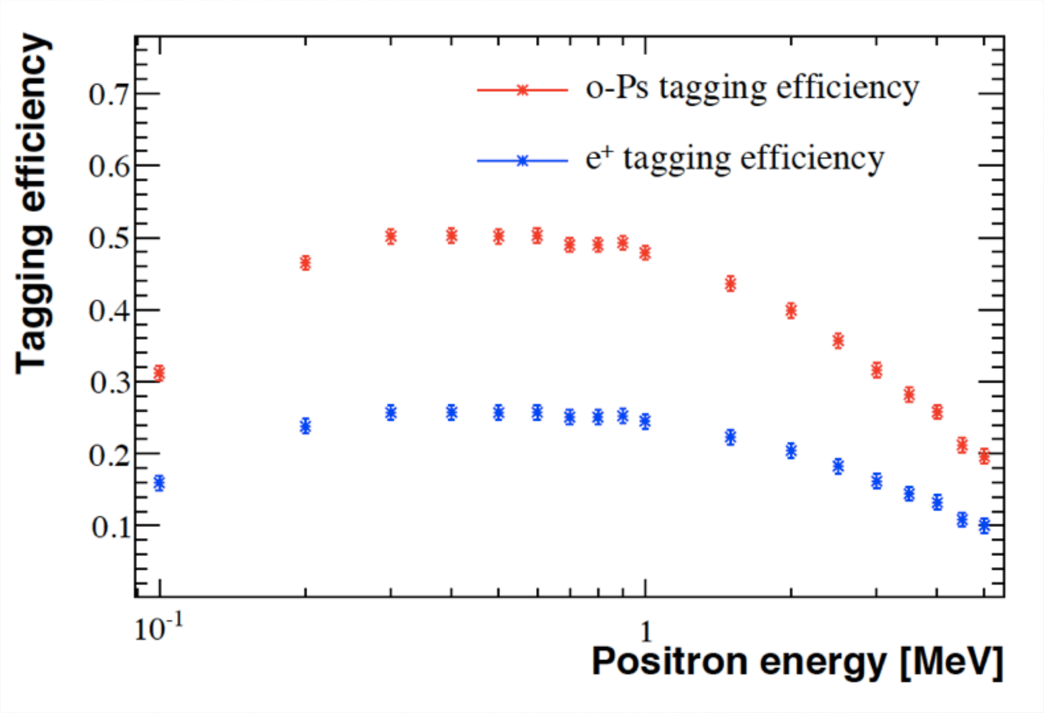
N_{oPs} ~ 50%

N_{e-} ~ 1%

PSD dependence on the energy

PSD optimization by varying **ϱ_0(E)** threshold, in order to accept **1%** of electron rejection

Total e+ tagging **efficiency =**
o-Ps formation **probability x**
PSD **efficiency**



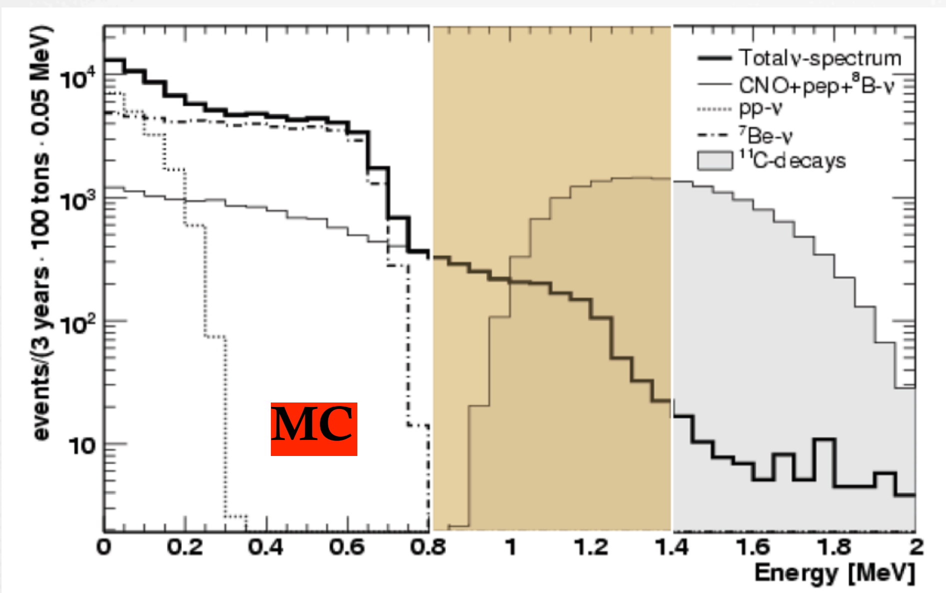
With this **"rough"** technique, **up to ~25%** of positrons are **tagged**

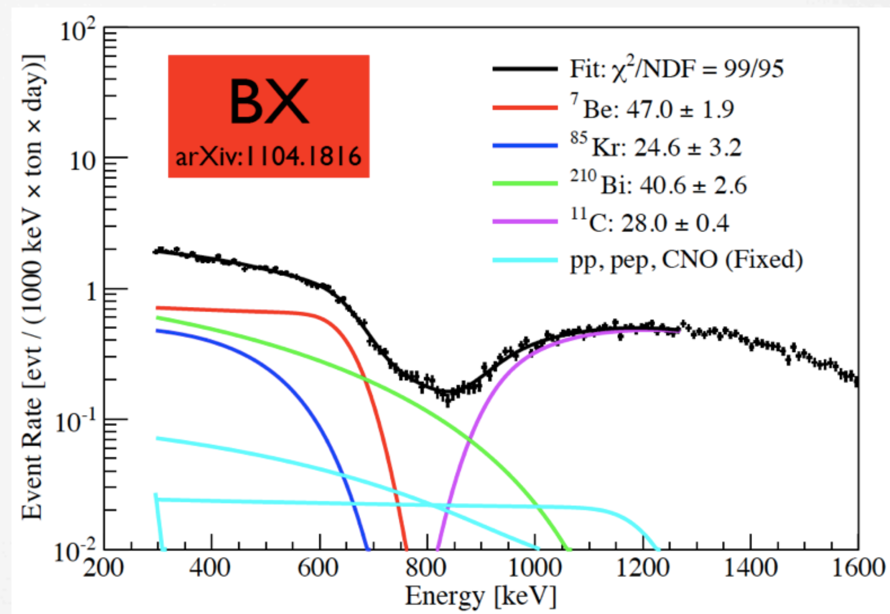
o-Ps PSD is effective in discriminating (a subset of) **positrons**

o-Ps PSD in Borexino: *pep* neutrinos

Presented in TAUP 2011 by Cristian Galbiati

Solar pep neutrinos: small branch (0.23%) but at the top of the *pp* chain
Main background: cosmogenic ^{11}C (positron emitter)

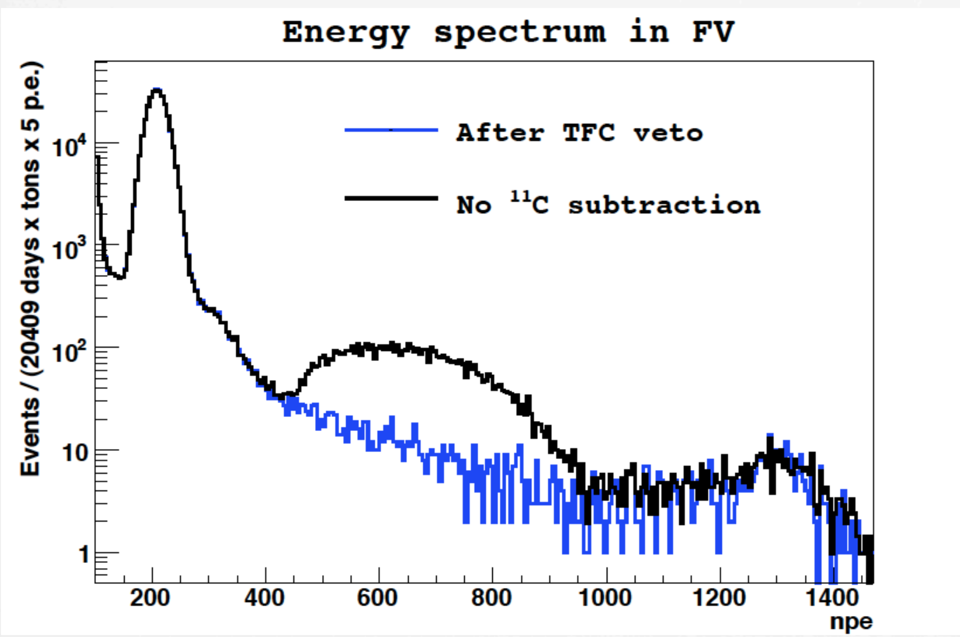


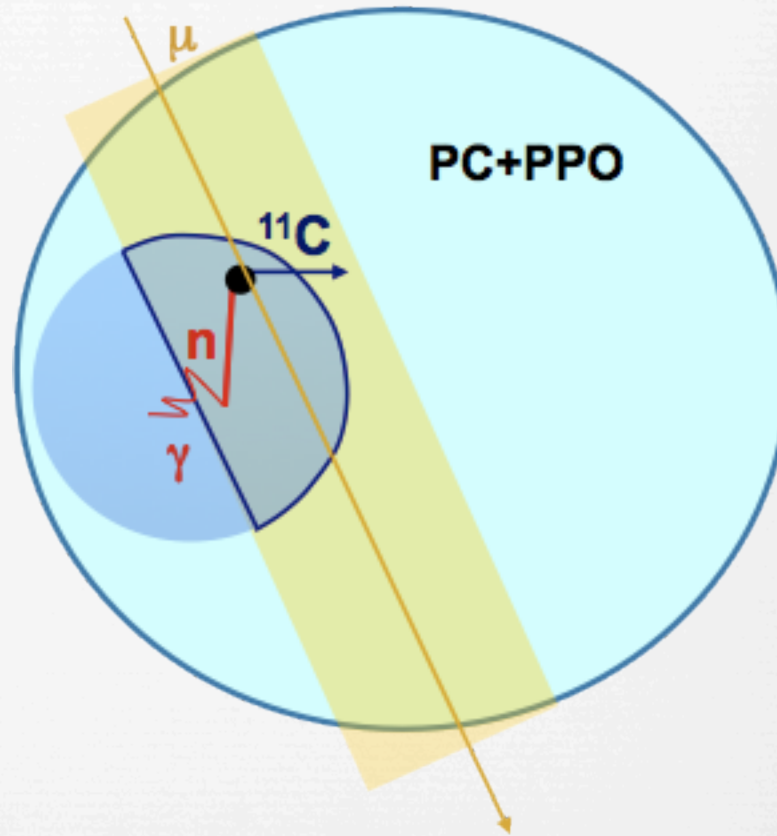


Positron Sample From Cosmogenic ^{11}C

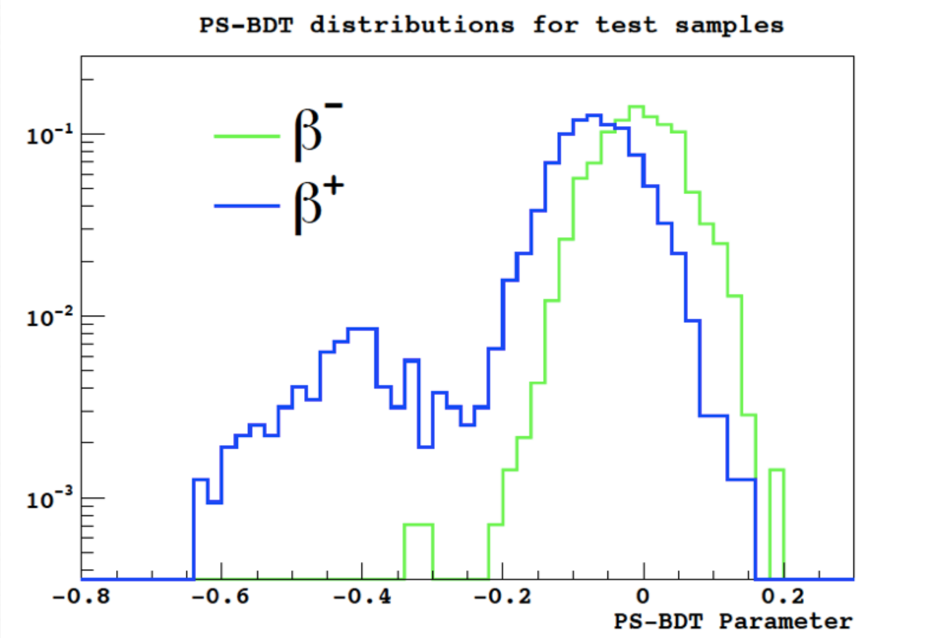
The Three Fold Coincidence among:

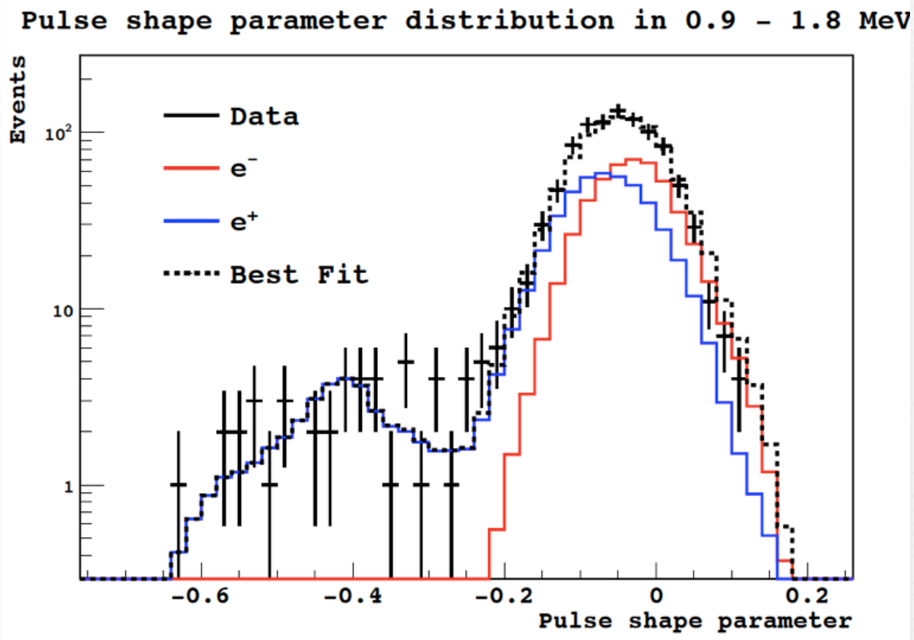
μ (secondaries) + $^{12}C \rightarrow \mu$ (secondaries) + ^{11}C + n
n + p $\rightarrow$ d + **2.2 MeV γ** (230 μs)
$^{11}C \rightarrow {}^{11}B$ + e^+ + ν_e (30 min)



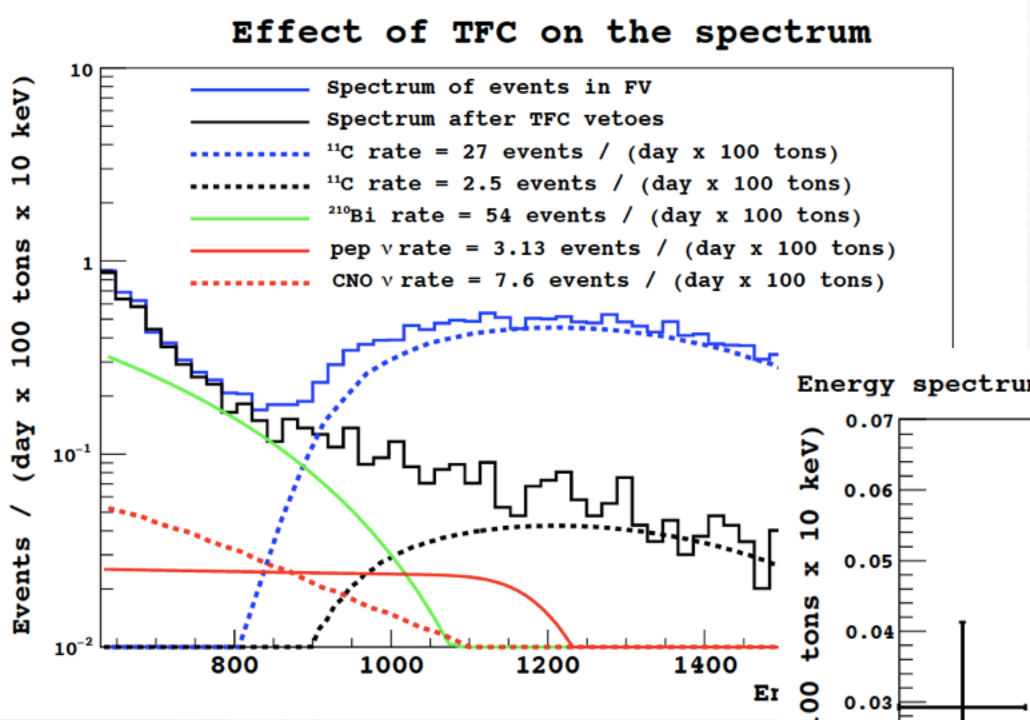


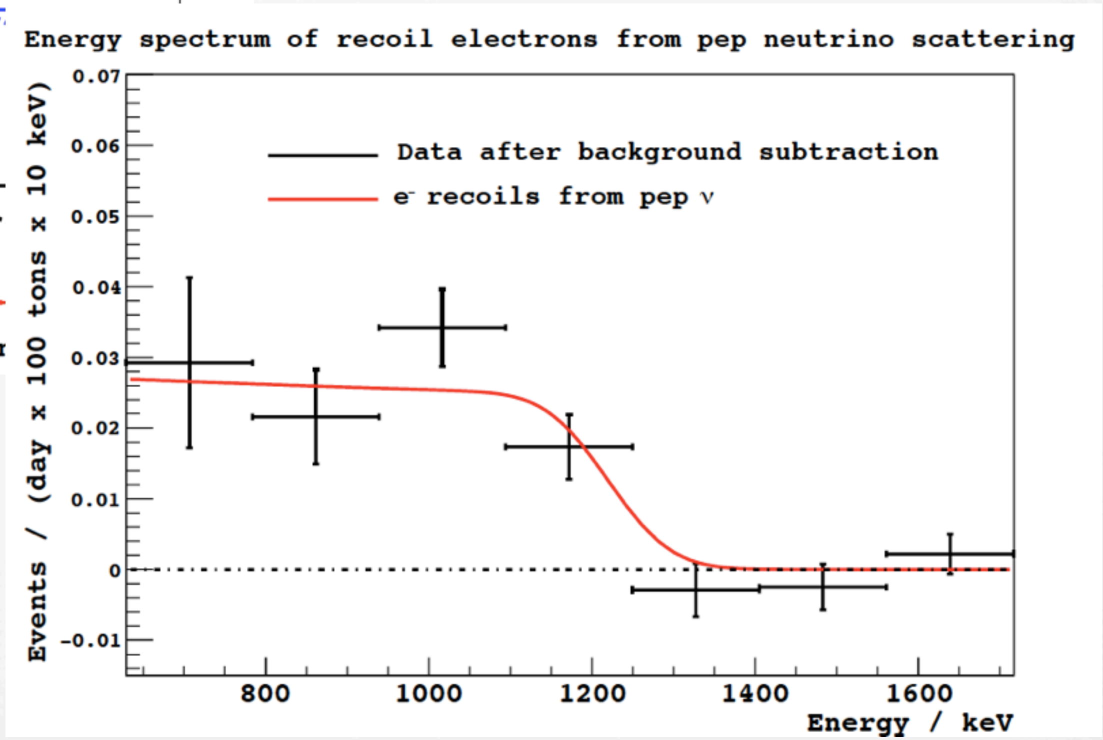
o-Ps PSD in Borexino





pep neutrinos in Borexino





Conclusion

- **o-Ps in liquid scintillators** has a mean life of **~ 3 ns** and formation probability **~50%**

- The delay between positron ionization and gamma induced Compton electrons is an **optimal signature for discriminating e^+/e^-**

- The o-Ps technique has been **successfully applied in Borexino**

- Near future: **effects of dopers** (Gd, Nd, ...) on o-Ps characteristics in liquid scintillators

- Far future: o-Ps in **plastic scintillators (?)**

New R&D project

νToPs

Neutrino Tagging with o-Ps
just funded by ANR JC